Is malaria control profitable? Return on investment of residential fumigation at a sugarcane processing facility

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1. Introduction

Malaria accounts for a half million annual deaths worldwide (Ashley et al., 2018; White et al., 2014; World Health Organization, 2019). Though rapid improvements in technology and funding have led to important reductions in malaria's global burden, the scale-up in activities required for elimination will mean new partnerships and actors. One promising potential stakeholder in global malaria eradication is the private sector, given its omnipresence and potential to benefit directly from the elimination of malaria. But little evidence exists demonstrating how private sector entities can engage with malaria control and benefit at the firm level.

The evidence of malaria's negative effects on health and wealth are amply described in the public health and economics literature. However, very little exists in the literature examining the costs and benefits of malaria control from a private ledger perspective (ie, the point of view of a business investor). Unlike a government or individual, a private firm investing in malaria control may be most interested not in its long-term macroeconomic effects, nor its short-term personal health effects, but rather on the impact on productivity (and the extent to which that productivity benefits accrue to the firm), absenteeism, and the opportunity costs of expenditures in malaria control. Importantly, since private firms do not capture (in terms of financial benefit) many of the positive externalities of a reduction in malaria, much of the existing literature on the economic benefits of malaria control are not applicable. In other words, though the benefits of malaria control are large (exceeding costs by a factor of up to 20 (Jamison et al., 2015)) and well known, the portion of those benefits accrued by a private firm investing in malaria control is unknown.

To address the question of the profitability of malaria control activities from the standpoint of a private firm, we analyze administrative data during a 4 year period from a private sugar facility in Southern Mozambique. We use absenteeism, which is directly correlated with the productivity losses associated with malaria infection, as our outcome of interest. We assess the effect of preventive malaria technology - in the form of indoor residual spraying (IRS) - on absenteeism, and demonstrate that the firm’s engagement in malaria control not only improved worker health, but also generated positive economic returns for the firm.

Since a worker's likelihood of absence is moderated not only by whether his/her home has been fumigated (ie, treated with IRS), but also by the time since fumigation as well as the fumigation status and proximity of neighbors' homes, we employed a time-discounted "community protection" concept in which an individual’s protection status is the distance-weighted average of all nearby households' protection status, weighted by proximity to the individual in question and declining quasi-linearly over the course of the effectiveness period of IRS (approximately 12 months). We regress absence against this "community protection" score, adjusting for both individual fixed effects as well as the lagged precipitation. Having estimated the effect of community protection on absence, we then run a series of scenario simulations to generate hypothetical community protection scores with different fumigation strategies, and convert the estimated absence rates, as well as associated program costs, into returns on investment.

We find that the firm's indoor residual spraying program is associated with a 3.7 percentage point reduction in absenteeism from 13.0% to 9.3%. This reduction is concentrated primarily among permanent workers who both benefit more significantly from IRS' absenteeism-reducing effect and make up a larger share of the workforce in terms of days worked. We estimate that the savings from reduced absenteeism outweigh the costs, with a program-wide return on investment of 100%, assuming daily wages of temporary workers to be approximately $7 and permanent workers to be approximately $10. Our analysis is intentionally restrictive, excluding any long-term or secondary benefits accrued from the improved health status of workers. Our scenario comparison suggests that this figure could be optimized, but is already near the top-end of its potential. We attribute the observed program optimization to the fact that the program already incorporates a relatively large degree of flexibility in its fumigation operations (ie, an area may be prioritized for fumigation if residents complain of mosquitoes, or if multiple residents fall ill with malaria). The lack of a fixed structure to program operations appears not to be a program flaw, but rather the reflection of flexible responsiveness to constantly-changing entomological and epidemiological realities.

This study does not endeavor to expand the current body of knowledge regarding malaria's ill effects on individuals and societies; rather, it aims to provide empirical evidence pertaining to a facet of malaria economics with very little in the literature: malaria control from a private-sector investment perspective. Our study adds to the existing literature by showing the effect of specific malaria control interventions on worker absenteeism, and translating that effect into a return on investment. Unlike in previous studies on the effectiveness of malaria control interventions (which generally find a positive effect, albeit subject to potential ecological bias, and analyzed at the level of society rather than the firm), we focus solely on one firm carrying out one intervention, taking advantage of individual-level data, and analyze results from a ledger perspective.

This paper is organized as follows. Section 2 describes the background on malaria, its economic burden, the role of the private sector in its control, specifically in Mozambique and at the firm itself. Section 3 describes the data we collected, variables of interest, our identification strategy for estimating the program's effect, and the conceptual challenges to modeling interventions with a high-degree of "spillover". Section 4 gives an overview of results and counterfactual scenarios, and Section 5 concludes.

2. Background and setting

Malaria's economic burden and prevention

Malaria has a large economic impact. At both the individual (Cole and Neumayer, 2006) and collective (McCarthy et al., 2000) levels, it affects behavior related to saving and investment. In the short-term, malaria reduces one's ability to work and imposes a financial burden both on oneself as well as caretakers (Ajani and Ashagidigbi, 2010; Asenso-Okyere and Dzator, 1997), and affects risk perception, productivity, absenteeism (Nonvignon et al., 2016), human capital accumulation (Castel-Branco, 2014), mortality, and costs of care (Sachs and Malaney, 2002).

There is ample economic literature on malaria's negative effect on gross domestic product (GDP and growth (Hong, 2011; McCarthy et al., 2000; Orem et al., 2012; Sachs and Malaney, 2002). Historical quasi-experimental studies have shown that malaria elimination leads to immediate improvements in under-five mortality, as well as increases in average years of schooling and the likelihood of employment later in life (Barofsky et al., 2015). Successful elimination campaigns in diverse settings have been shown, via quasi-experimental studies, to significantly improve lifetime female educational attainment (Lucas, 2010). The gains from malaria elimination go beyond education. While Barofsky showed immediate improvements in males' ability to find wage work following an elimination campaign, Bleakley showed long-term gains in adult labor productivity and income as a result of decreased exposure to childhood malaria (Bleakley, 2010). This is in line with Cutler's study on malaria elimination in India, which showed significant gains in household consumption following a 1950s elimination campaign (Cutler et al., 2010). Though Cutler did not find the educational gains common to most elimination studies, studies with more granular data on education, such as Thuilliez's 2010 longitudinal analysis of Malian schoolchildren, suggest that malaria reductions lead to decreased absences, and improved educational outcomes (Thuilliez et al., 2010).

These studies make a strong case for malaria's high economic costs and the corresponding benefits of its elimination or reduction. But they focus on these benefits from a purely *societal* perspective; that is, they strive to quantify the gains in both health and wealth to society itself, rather than to the hypothetical funder of the intervention. They find that the benefits likely outweigh the costs of the intervention, but this should come as no surprise since (a) malaria control and elimination initiatives are relatively affordable at scale and (b) the public welfare perspective allows for the incorporation of long-term, aggregate-level benefits in education and the economy, even though these benefits are disperse and relatively small at the individual-level. Even more recent studies on targeted campaigns generally look at societal-level benefits in the form of disability-adjusted life years (DALYs), days of lost productivity, etc. (Howard et al., 2017). These studies, unanimous in their conclusions that malaria's elimination has large non-health benefits, do not differentiate between the direct beneficiaries (such as the recipient of a household-level malaria control intervention) and those who indirectly benefit through positive externalities (their neighbor), nor do they take on an investment perspective (other than that of the "investor" as society itself).

The role of the private sector in malaria control

From the perspective of the private sector, however, investing in malaria control is not so clear-cut, since the benefits are often disperse, long-term, and difficult to quantify. Public health interventions targeting malaria - and their corresponding cost-effectiveness evaluations - most often focus on impacts pertaining to public welfare, such as an increase in life years adjusted for disability or quality (Gunda et al., 2016; Gunda and Chimbari, 2017; Hanson, 2004). Though population-level health is certainly of importance to businesses, and improvements in health incidentally improve the economy at all levels (Vecchi et al., 2013), these improvements may be too dispersed or long-term to incentivize private sector involvement in health campaigns. In other words, the returns for malaria control are less for the private sector because (i) they capture only part of the benefits and (ii) the private sector does not benefit from the positive externalities.

Just as the benefits of malaria control to the private sector are more limited than those to the country as a whole, considerations regarding costs for a firm are also distinct than those for a government. Though many firms in endemic regions engage in malaria control programs, this should not be considered, per se, evidence of its cost-effectiveness (since the extent to which corporate social responsibility plays a role is unknown) (Joe Brew Celine Aerts, n.d.).

The literature on private sector malaria control

In general, large firms operating in malaria endemic regions consider malaria to be an important enough issue to merit at least some investment (Pluess et al., 2009). Several studies examine the effect of foreign firms engaging in large-scale malaria control campaigns (Han, 2015; Kaula et al., 2017). AngloGold-Ashanti, in partnership with local and national government in Ghana, invested in a well-rounded malaria control program in 2005, and saw worker absenteeism fall by 50% in 13 months (Ccm, 2016). Lafarge's simultaneous investment in a comprehensive malaria control program in Benin was associated with an average 41% reduction in absenteeism among workers over the course of 4 years (Ccm, 2016; Egedeye et al., 2011). Zambia Sugar Plc, Zambia's largest sugar processing facility, saw annual malaria cases at its company clinic fall from nearly 3,000 in 2001 to less than 500 by 2005, following investment in a malaria control program. Marathon Oil's investment of 15 million US in vector control, education, net distribution and malaria treatment on Bioko Island in Equatorial Guinea lead to an estimated 95% reduction in the number of parasite-infected mosquitoes and 50% reduction in malaria incidence among young children (Asquino, 2016; Overgaard et al., 2012). A PATH study in Zambia found a return on investment of 28% among three companies investing in employer-based malaria control (Mouzin and Al., 2011).

Though certainly suggestive of high returns on malaria control investments, these studies generally consider population health as the outcome measure of interest, rather than worker absenteeism or productivity. They are also mainly trend analyses, lacking well-defined causal identification strategies. Similarly, they often neglect to differentiate between those clinical costs which are absorbed by the local health system versus those which are absorbed by the firm itself. When absenteeism itself is considered, the apparent effects of malaria control have generally been found to be high, but causation is difficult to establish, given that the previous studies rely on aggregate data.

Importantly, two previous studies do utilize worker-level data to estimate the effect of malaria control on productivity. A World Bank analysis of Nigerian sugarcane cutters found that the simple availability of testing and treatment increased productivity by 10% in the weeks following the provision of services, the conclusion being that both the treatment and the test result were effective in increasing productivity, the latter simply increasing the information available which could influence personal labor allocation decisions (Dillon et al., 2014). A randomized controlled trial (RCT) in Zambia showed an even greater effect from investments in preventing malaria, using individual-level data: farmers given bed nets saw fewer days lost to illness (both directly and due to caretaking responsibilities for ill family members), translating to an increase of approximately 15% in crop yield(Fink and Masiye, 2015). Though compelling, the Nigerian program only dealt with medical services (diagnostics and medication), rather than preventive interventions, and the Zambian RCT examined individual farmers, rather than estimating benefits to a firm.

A multitude of studies have examined the effects of other diseases, such as HIV/AIDS, on productivity and wealth (International Labour Organization, 2002; Ruger, 2004; Ruger et al., 2012; Sendi et al., 2004; Stillwaggon, 2005). There have also been numerous analyses of the feedback loop between wealth and health in developing countries (Asenso-Okyere et al., 2011; Devkota and Upadhyay, 2013; Farrell, 2006; Hussain and Perera, 2004; Kirigia and Muthuri, 2016; Laxminarayan, 2007). In general, infectious disease is associated with significant reductions in productivity, whereas initiation of treatment has the opposite effect (Thirumurthy et al., 2005). Though relevant, these studies generally look at diseases with a longer-term natural history, do not take into account prevention or treatment costs, and take on the perspective of the public sector (as opposed to a private investor), accordingly considering as "benefits" in the cost-benefit equation many effects which accrue outside of the strict realm of the private actor.

In the literature, making the “investment case” for malaria control or elimination generally implies that the investor is the public sector, and takes into account those costs and benefits which are applicable from a public welfare point of view (Shretta et al., 2017). For example, an economic analysis by the Corporate Alliance on Malaria in Africa on the Bioko Island Malaria Control Program found a 4:1 cost-benefit ratio, but the perspective in this case was considered to be the “community” (Egedeye et al., 2011). Though appropriate in most cases to consider benefits accrued to the community (the government or institutions interested in public welfare primarily being the primary malaria control agents in most locations), the findings of these studies are rarely applicable to the private sector, and even less so at granular levels (such as an individual firm). In the case of a private firm not engaged in “corporate social responsibility”, it is not clear whether investing in malaria control would be profitable or not. This lack of clarity not only may discourage private investment in malaria control, but also makes it difficult for governments to pinpoint the correct amount of subsidy (if applicable, such as in the case of a government wanting to incentivize large firms to take care of their workers’ health by offsetting part of the cost of doing so) to encourage private sector scale-up in malaria control (Alonso et al., 2017).

The literature on the effect of sugarcane cultivation on malaria risk is mixed. While some studies have found that the prevalence of malaria vectors in sugarcane areas to be similar to that of uncultivated areas (and less than in areas dedicated to other forms of more water-intensive agriculture, such as rice) (Ijumba et al., 2002), other studies have found significant increases in factors associated with malaria transmission at large-scale sugarcane facilities relative to traditional, small-scale farming and non-irrigated farming (Jaleta et al., 2013). Regardless of the effect the presence of a sugarcane farm *per se* on local malaria epidemiology, the time spent outdoors by sugarcane workers, the fact that many workers are migrants, the socioeconomic status of manual laborers, and their sometimes precarious housing situations, all suggest that sugarcane farmers are likely at increased risk of malaria infection (O’Laughlin, 2016). This is important, given that even among occupations with far less inherent exposure to mosquitoes (such as health professionals), malaria is one of the primary causes of work absenteeism in malaria-endemic countries (Burton et al., 1999). There is also some concern regarding the effect of large-scale insecticide use - common at essentially all Sub-Saharan African sugarcane farms - on insecticide resistance among mosquitoes in the area. A study in Belize found that mosquito populations on the edge of sugarcane fields had higher tolerance to insecticide than similar populations in the core of fields or outside of the periphery (Dusfour et al., 2009). Sugarcane areas may offer the standing water necessary for mosquito breeding, but also perhaps attract mosquitoes which would otherwise be elsewhere, due to compounds in sugarcane pollen (Wondwosen et al., 2018).

Malaria in Mozambique

100% of the Mozambican population are at risk of malaria, living in what the WHO classifies as a “high transmission” area (Moonasar et al., 2016; World Health Organization, 2019). Annually, Mozambique has more than 8 million clinical malaria cases (an annual incidence of approximately 300 per 1,000 residents), with an estimated 14,000 deaths. Malaria accounts for 29% of all deaths, and 42% of deaths among those under five years of age (INE, 2011). Since 2013, Mozambique has seen a gradual increase in the incidence of malaria (Moonasar et al., 2016). 100% of the malaria in Mozambique is of the Plasmodium falciparum species, with Anopheles funestus, gambiae, and arabiensis as the primary mosquito vectors of the disease (WHO, 2015).

Poverty is rife in southern Mozambique, and its associated illnesses take their toll on the population. The community prevalence of HIV/AIDS is as high as 40% (González et al., 2012); even in a more recent study suggesting a much lower prevalence of 22%, the risk of infection is still twice that of nearby areas (Mocumbi et al., 2017). Recent years have seen a three-fold increase in tuberculosis (García-Basteiro et al., 2017). Malaria, which has the greatest mortality burden due to the fact that the young are especially vulnerable to its effects, is perennial, though worse during the rainy season (December - March) (Saúte et al., 2003). Adult malaria prevalence is very high, albeit much of it asymptomatic (Mayor et al., 2007). In regards to worker health, malaria is Maragra's primary concern, being so important as to justify the existence of both an on-site testing laboratory and clinic, as well as a malaria control department.

A significant sector of the economy in Mozambique is dominated by large-scale foreign direct investment projects (Castel-Branco, 2014; Robbins and Perkins, 2012), and the role of the private sector in health generally, and malaria specifically, is unequivocally important. Large agriculture and extractive industry firms take up wide swaths of land and employ hundreds of thousands (German et al., 2013). The Mozambican state has encouraged large-scale enterprise with the aim of general economic development (Buur et al., 2012). And where large firms exist, they often take on social roles such as housing and health care (Buur et al., 2012; Winkler, 2013). At times, this role is necessary from a purely practical standpoint; in other cases, it is employed under the auspices of "corporate social responsibility" (Azemar and Desbordes, 2009; Curtis et al., 2003). Regardless of the language used, it is clear that private industry plays an important role in public health in Mozambique (Castel-Branco, 2014; Robbins and Perkins, 2012).

Study area

Sugar has been systematically cultivated in Mozambique since the late 1800s. The Incomati Estates company, a small sugarcane processing facility started by a Scotsman on the banks of the Incomati River in 1913, was the first firm to export sugar from Mozambique. Following its purchase by international investors in the 1950s, it (along with the rest of the industry) expanded significantly, exporting to both Europe and the United States. In the late 1960s, a Portuguese family opened the Maragra Açúcar company, while a group of foreign investors started the nearby Marracuene Agrícola Açucareira mill. By the early 1970s, sugar grew to account for greater than 10% of Mozambique’s national exports. Nationalized following independence in 1977, the industry’s production levels fell from 320,000 annual tons to fewer than 15,000 by 1992. After the end of the civil war, foreign investment revived the sugar industry, and by 2011 production had surpassed its 1972 peak.

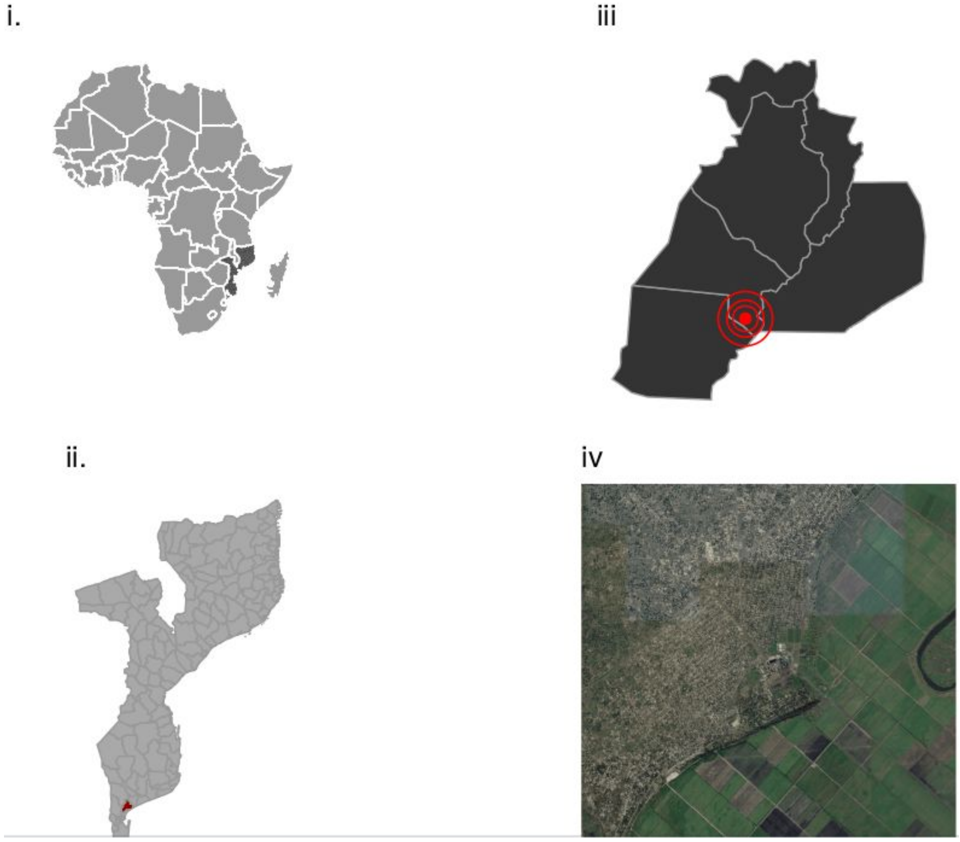

Figure 1. (i) Mozambique in Africa, (ii) Districts of Mozambique with Manhiça highlighted in red, (iii) District of Manhiça with Maragra highlighted in red, (iv) Maragra SA with surrounding fields and village

The mill of the Maragra Açucar SA (a subsidiary of the Illovo sugar company, henceforth referred to as "Maragra") was nationalized in the 1970s (like all other Mozambican mills), went through a period of low production, and then fell completely out of use by 1984. It re-opened in private hands in 1992, and was renovated by a group of international investors in 1998. Today, Maragra accounts for roughly one quarter of Mozambique's overall sugar production (second only to the nearby Xinavane mill run by the Hulett Sugar Tongaat company) (Sutton, J., Mapa empresarial de moçambique). With a favorably close location to the port of Maputo, ample land (approximately 90 square kilometers of plantation, and 5 squared kilometers of factory grounds), approximately 5,000 employees (of which three quarters are seasonal), and a mill with the capacity to process not only all the sugarcane grown on Maragra's land, but also the cane of the many nearby smallholders (O'Laughlin, 2016), Maragra has so far been able to weather the 2016 Mozambican crisis and concurrent collapse in global sugar prices.

Maragra (figure 1, panel iii) is located in the district of Manhiça (figure 1, panel ii), a semi-rural area in the south of Mozambique (figure 1, panel i). 80 kilometers north of the Mozambican capital of Maputo, the district is low-lying, consisting largely of savannah and wetlands along the Incomati River. Most of the area's 160,000 residents (Sacoor et al., 2013) work as subsistence farmers. Migration from the area to South Africa for the purpose of employment in the profitable construction industry is common, especially among men (Nhacolo et al., 2006), as is migration to the area (from other parts of Mozambique) for seasonal work on the sugarcane plantations at Maragra and the slightly larger facility in Xinavane (at the district's border with Magude) (O'Laughlin, 2016).

Maragra workers are mostly seasonal, working for the firm approximately half of the year during harvest time, and cultivating crops, working in construction, or going unemployed (or working elsewhere) during the other half. Though many workers live "on-site" (ie, within the delineated property of the firm itself), a sizable minority resides in the environs (figure 1, panel iv). For workers living on-site and their co-residing family members, Maragra provides indoor residual spraying (IRS) using ACT (alpha-cypermethrin) and DDT (Dichlorodiphenyltrichloroethane), the former being applied preferentially to areas closer to the fields.

3. Materials and methods

Data collection

In collaboration with the sugar processing facility, we collected administrative data for the four year period from January 2013 through December 2016. Data came from four sources: (i) the Human Resources' roster of worker details and absences, (ii) the facility's on-site clinic's medical and laboratory records, (iii) the facility's on-site malaria control program's records pertaining to the dates, chemicals, and location of IRS activities, and (iv) interviews with company employees pertaining to costs, data limitations, etc. Digitization and collection of data took place during the period from March 2016 through May 2017. Supplementary data pertaining to worker characteristics was obtained from the Centro de Investigação em Saude de Manhiça's (CISM) demographic census, which covered workers from the district, but not those who recently migrated from other parts of the country (Nhacolo et al., 2006).

There is no publicly available weather station data specific to Manhiça district or the Maragra facility. Therefore, we retrieved weather data for all Mozambican stations from NOAA and estimated daily precipitation at the centroid of Manhiça using a simple interpolation method whereby the district's weather conditions were estimated to be a function of all Mozambican weather stations' reported conditions, inversely weighted by kilometers from district centroid.

Maragra regularly employs IRS at on-site worker households in order to reduce those workers' (and their families') risk of malaria infection. IRS works both by killing the malaria vector (mosquito) and deterring it from approach, thereby preventing infection of the household occupants (Oxborough et al., 2019). When administered correctly, IRS is a low-risk intervention to its recipients, and is assumed not to affect absenteeism in the short-term (to the extent that it may cause negative side-effects, these are generally long-term) (Eskenazi et al., 2019; Murray et al., 2018). It is preventive only, and does not cure current malaria infection, nor does it affect the parasite load of living mosquitoes. Workers living off-site (our control group) also may have received IRS at some point during the study period (from government programs). Even though we do not have reliable person-level data on IRS carried out by the government, off-site workers are a suitable control in the sense that they represent “business as usual” (ie, what would happen if the company carried out no IRS and relied solely on public interventions). Using company HR and clinical records, we were able to identify all-cause absences and episodes of clinical malaria among all workers, as well as identify the time since the most recent IRS episode before the onset of absence or illness.

Worker characteristics, illness and absenteeism data, along with IRS activity data (when each house was sprayed and with which chemical), were systematically collected, stored, and used at the individual level by the company, and therefore of generally high quality. Because cost data was less systematically collected by Maragra, and because many costs could not be precisely quantified due to the abundance of in-kind and cross-departmental expenditures, we had to rely on estimations based on a mix of interviews, receipts, and interpolations. Additionally, wage data for some employees in higher-level positions was not available due to privacy concerns. Since our program cost data is not as reliable as our worker characteristic and outcome data, we were conservative in our estimates, and generally tried to err on the side of inclusion when doubt was aired regarding whether to include program activities and materials into program costs. Cost data consisted of three types: (i) wages of malaria control employees, (ii) transportation and vehicle costs for IRS teams, and (iii) acquisition costs of purchasing IRS chemicals for fumigation (ACT and DDT).

Descriptive statistics

We collected absenteeism and demographic data on 3,915 workers with known residence from 2013 through 2016. Workers were approximately 60% male, and 75% fieldworkers (the remaining being mostly factory and administrative workers). Most were in their 20s and 30s (72%) and employed on temporary contracts (76%). Temporary workers tended to be younger and male; female temporary workers being on average 5-10 years older than their male counterparts. Permanent workers had a bi-modal age distribution, the older peak explained by the greater density of males in administrative roles. Females accounted for 43% of temporary workers but only 16% of permanent workers. Due to a lack of data availability regarding contract end dates in 2016, and data reliability issues for 2013, we had to exclude from our analysis all temporary workers for the years 2013 and 2016. The breakdown of the number of observations for different demographic / worker groups in Table 1 (below) differs slightly from the above since the unit of observation in the table is worker-days, rather than workers.

	2013 (n=276650)	**2014 (n=439387)**	**2015 (n=559352)**	**2016 (n=261101)**	**Overall (n=1536490)**
Worker location					
Field worker	103674 (37.5%)	240043 (54.6%)	339467 (60.7%)	79715 (30.5%)	762899 (49.7%)
Not field worker	172976 (62.5%)	199344 (45.4%)	219885 (39.3%)	181386 (69.5%)	773591 (50.3%)

Worker contract					
Permanent	276650 (100%)	282413 (64.3%)	289602 (51.8%)	261101 (100%)	1109766 (72.2%)
Temporary	0 (0%)	156974 (35.7%)	269750 (48.2%)	0 (0%)	426724 (27.8%)
Worker sex					
F	46192 (16.7%)	86319 (19.6%)	132532 (23.7%)	41756 (16.0%)	306799 (20.0%)
M	230458 (83.3%)	353068 (80.4%)	426820 (76.3%)	219345 (84.0%)	1229691 (80.0%)

Table 1. Observed worker-days by year and worker characteristics.

During the study period, weather followed typical seasonal trends for the area, albeit slightly drier than previous periods.

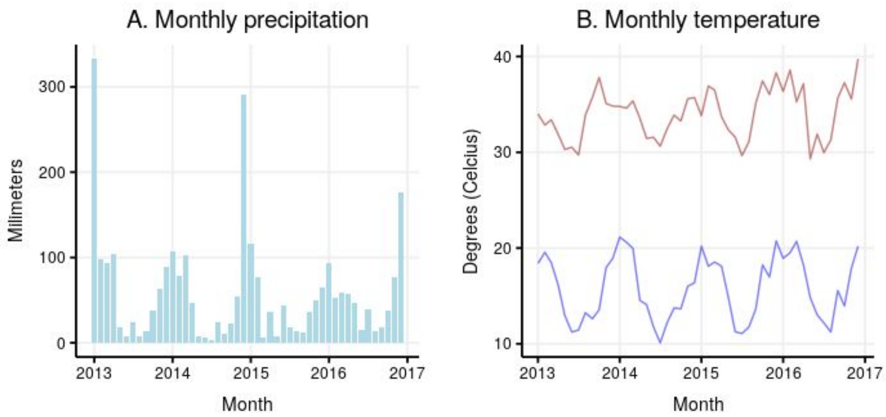

Figure 2. Monthly total precipitation in the Maniça district; B. Monthly maximum (red) and minimum (blue) temperatures.

In Southern Mozambique, malaria peaks during the summer months (December through March) most years (Figure 2, panel A), and worker absenteeism rates (figure 3, panel B) track district-level malaria incidence (Figure 3, panel A) closely, following the same seasonal weather patterns (figure 2, panel B). Both all-cause absenteeism and sick absenteeism have declined in recent years at Maragra (figure 3, panel C), with the latter declining at a faster rate than the former. The fact that the rate of confirmed cases at the company clinic is largely non-seasonal (figure 3, panels E and F) suggests that a significant portion of workers either seek care for malaria elsewhere (for example, government health posts, of which several are nearby and in some cases closer to workers' residence than the company clinic) or do not seek care at all during malaria infection. Accordingly, we focus our analysis on all-cause absenteeism rather than sickness absenteeism or malaria diagnostics, with the assumption that much of illness is captured by absenteeism but not by the clinical data.

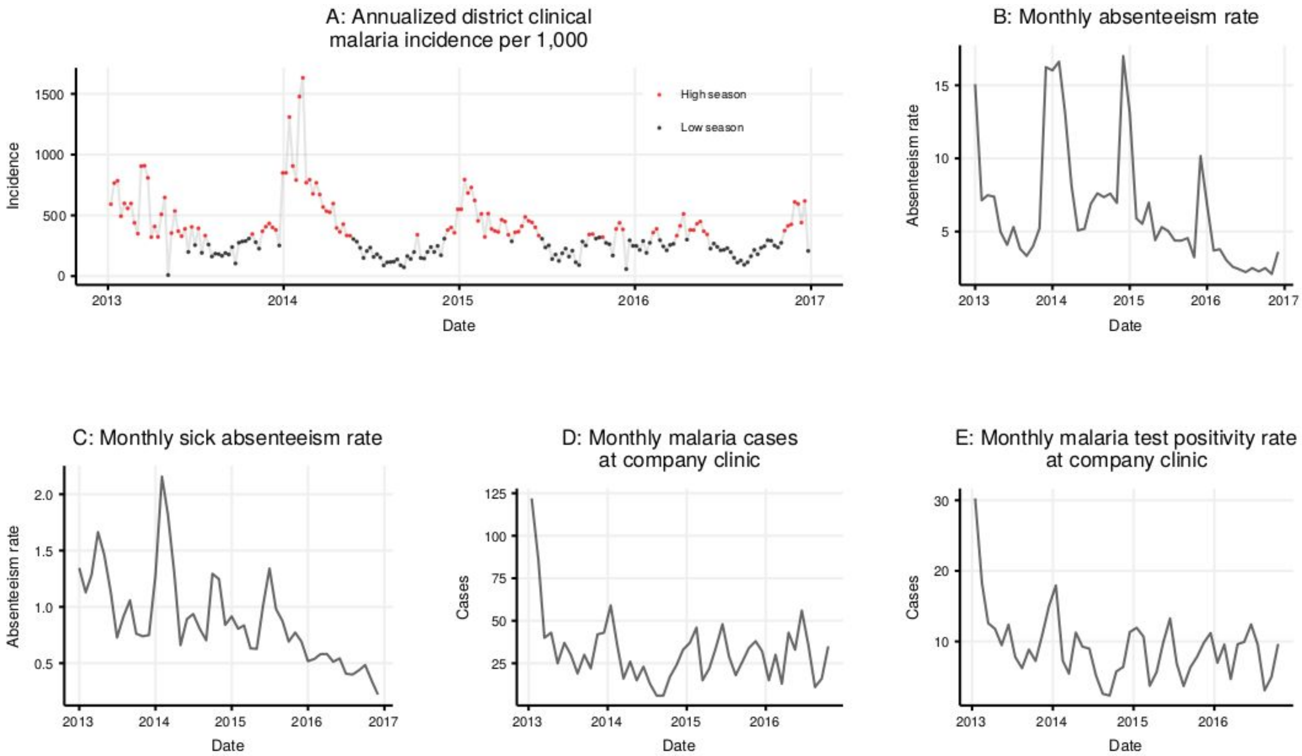

Figure 3. (A) Clinical malaria (district of Manhiça), (B) all-cause absenteeism among Maragra workers, (C) sick absenteeism among Maragra workers, (D) positive cases at company clinic, and (E) test positivity rate at company clinic

Fumigations: During the period from January 1st, 2013 through December 31st, 2016, the Maragra Malaria Control Unit carried out 11,007 episodes of fumigation of residential "agregados" (households), for a total of 13,260 building-fumigation combinations. The total number of unique agregados sprayed during this period was 3,998.

	2013	2014	2015	2016
Households fumigated	1170	2336	2963	2019
Fumigations	1235	3283	4303	2186
Percent of households fumigated	28.92	57.73	73.23	49.9
Mean fumigations per fumigated household	1.06	1.4	1.45	1.08

Table 2: Fumigation activity by year

IRS activities, managed by Maragra's Malaria Control program, are ongoing throughout the year, albeit with significant variations in activities by month (Figure 4, panel i). Most on-site houses are sprayed, though the time between fumigations is irregular (Figure 4, panel ii). Off-site houses may also receive IRS (managed and carried out by the National Malaria Control Program), but the status and timing of these fumigations is not known at the individual level. Though we do not have data on the non-residential workers (who we consider as the "business as usual" control group), they are included in our models because they provide useful information pertaining to the effect of seasonality.

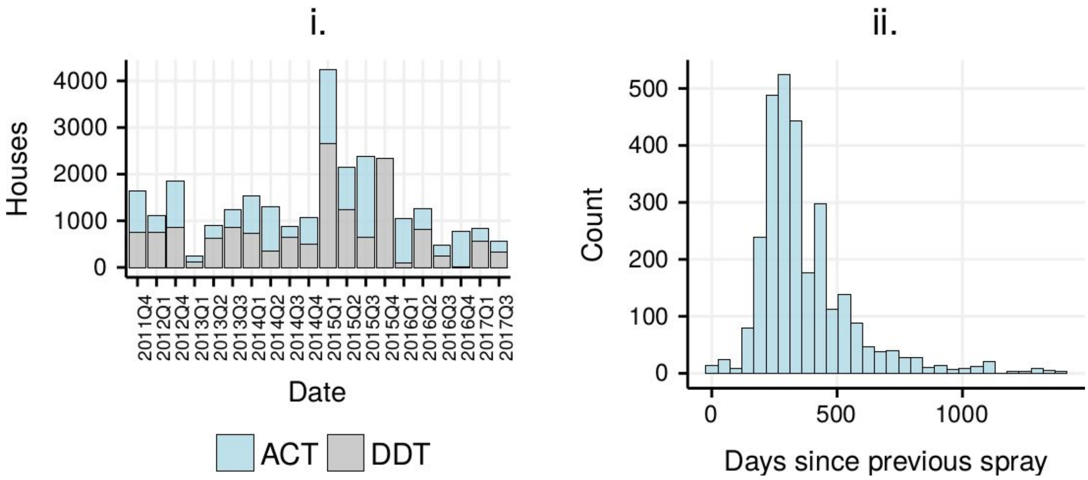

Figure 4. (i) Fumigation activities carried out by Maragra Malaria Control during study period, (ii) Distribution of average time between sprayings of households

Costs of program: The malaria control program at Maragra has an average annual operating budget of approximately $76,500, which includes the purchase of insecticide, the wages of IRS sprayers and drivers, transportation, record-keeping, and general administrative costs. Assuming linearity in costs, the program spends approximately $23 per building sprayed[1]. Much of the benefit of IRS goes to non-worker residents (such as familiy members) of sprayed agregados (who constitute a majority), but this benefit is purposefully ignored for this analysis, since our focus is solely from an internal accounting (ie, profit) perspective. Costs by category varied widely by year (figure 5).

[1] $76,500 is the *average* total Malaria Control department's budget for the years observed. $23 is the result of dividing the average number of households sprayed into the budget.

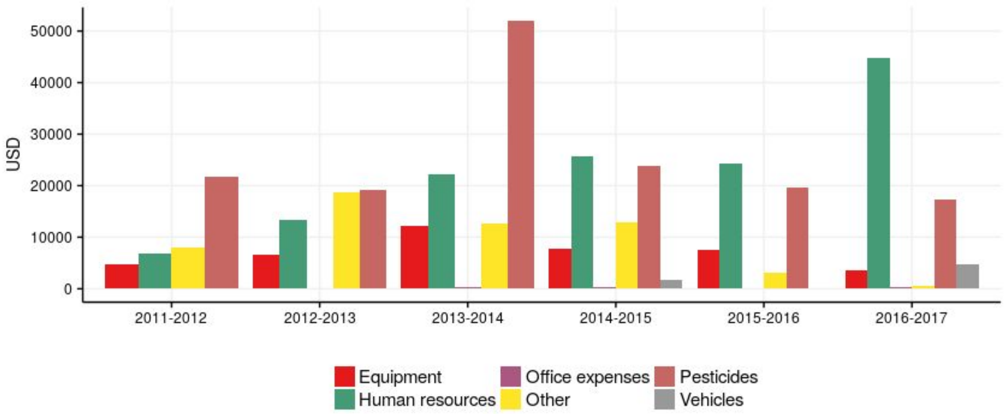

Figure 5: Operating expenses related to the malaria control program

Cost of malaria: Given the fact that clinical data does not fully capture all malaria-related absences (both for the possibility for workers to go to non-company public health clinics in the area and for looking after family members who have malaria), our main focus on quantifying the costs of malaria is through excess all-cause absenteeism. For the purpose of simplicity, and lacking a better measure of productivity, we simply consider that an absence costs the company the wage of that worker. For clinical savings, we estimate the number of absences which result in one positive clinical malaria case at the company clinic (80), apply the estimated treatment cost ($31.49 as per (Ezenduka et al., 2017)) to the equivalent share of prevented absences, and convert that figure into a daily cost. We intentionally ignore the savings accrued by the public health system, as well as the likely utility gains in secondary realms such as school absenteeism, productivity, etc.

Conceptual framework and identification strategy

Our aim was to estimate the effect of IRS on worker absence. By extension, we calculate return on investment. Our data allow us to link fumigation data at the household level to the absence rates of workers residing in that household. The protective effect of IRS on an individual residing in a fumigated household is assumed to be highest upon spraying and declines thereafter over the course of 12 months, at which time we consider the house to no longer be protected. This waning effect in protection is attributable to declines in a mosquito's likelihood of dying upon contact with a surface treated by IRS as well as the likelihood of being deterred from remaining in the area. Experimental observation of compounds treated by pyrethroids, ie ACT (Sherrard-Smith et al., 2018) shows that the waning effects in mosquito mortality and deterrence translate to a similarly quasi-linear increase in successful bloodfeeding episodes over the course of approximately one year. Our linear decay function for IRS' effectiveness assumes that DDT's effectiveness follows the same temporal patterns as ACT's, and fails to take into account insecticide resistance or potential interaction effects with ITN use, an interaction which has been shown in other studies to have important effects (Choi et al., 2019; Protopopoff et al., 2018). By the same token, this approach ignores potential compounding effects of IRS application over time as a function of timing relative to the malaria transmission season (Worrall et al., 2006), and does not take into account surface material, which may also impact insecticide effectiveness (Ngwej et al., 2019). Though only a rough proxy, our estimation for the function of the waning effect of IRS insecticides is in line with research based on direct observation of mosquito mortality (Tangena et al., 2013) as well as indirect observation of effectiveness based on the incidence of mosquito-borne illness (Bradley et al., 2012).

Since the presence of nearby IRS (even if not at one's own house) reduces the number of living nearby mosquitoes, we also consider the fumigation status of neighboring households as a protective factor against malaria infection. In other words, IRS application at one house has a positive externality at other nearby houses. This "spillover" effect would theoretically go through two channels: (i) via a reduction of mosquitoes in the vicinity and (ii) via a reduction of the malaria parasite in the blood of humans in the vicinity (ie, the parasite "reservoir").

In order to account for the fact that applying IRS has (i) a direct effect on the recipient (when the IRS is applied to the walls of his/her home), (ii) an indirect effect on the participants neighbors, and (iii) a waning effect over time, we devise a time-specific "protection" score based on the theoretical effectiveness of IRS, and then use that protection score to develop a time-place specific "community protection" score based on a weighted average of nearby household protection scores. We consider a household's "community" protection level (ie, the protection conferred to the house through externality) to be the contribution of the other houses' protection levels, weighted by the distance to the house in question. This approach, though failing to take into account the complex relationship between vector abundance and human density (Romeo-Aznar et al., 2018), accounts for the fact that fumigation of a household kills mosquitoes which otherwise would have made it into other nearby households.

We define community protection status as...

$$p_{it} = \sum_{j=1}^{N_i} w_{ij} F_{jt}$$

wherein...

$w_{ij} = \frac{1}{1+Dij}$, where Dij is the distance between household i and j in meters

$F_{jt} = max\,(0,\ 365 - nr\ of\ days\ since\ fumigation\ of\ household\ j)$

N_i = the number of households living in a 1 km radius of household i

An individual's total protection score at any given time is the sum of the indirect protection conferred by fumigating neighbors' households and the direct protection conferred by the fumigation of her household. The decision to devise a score for indirect protection conferred by others was motivated in part by findings from previous studies on positive health externalities in malaria interventions related to bednet coverage (Alaii et al., 2003; Escamilla et al., 2017; Stebbins et al., 2018). Our score is conceptually similar to Cohen and Dupas' quantification of the positive externalities of bednet use in Kenya (Cohen and Dupas, 2010) in that it attempts to estimate the protection conferred to "non-users" by "users" and is in line with Hawley et al's finding that the main driver of reductions in malaria following bednet distribution was not sleeping under the net, but rather the community-wide reduction in mosquitoes (Hawley et al., 2003). Though no studies exist on positive externalities for IRS coverage at the individual-level, to the extent that the mechanisms for the reduction in infection are similar to those of bednet (reduction in the natural reservoir of the disease, reduction in the number of nearby vectors, etc.), it is reasonable to assume similar effects. Our approach for estimating indirect effects of IRS differs from Hawley's estimation of bednets' indirect effects in that we incorporate a time dimension for the intervention's waning effect, requiring us to create community protection scores for every day-location pair. Also, unlike other studies which conceptualize community protection as a function of coverage in an area with an explicit cut-off (ie, 300-meters from the household in the case of Hawley, a cluster, village, or compound in most other cases (Stebbins et al., 2018)), and treat equally the relative contribution to indirect protection of all units within that cut-off, we aim to increase precision by weighting each neighboring households' contribution to any other household's indirect protection score by distance, with an intentionally high cut-off of one kilometer. Though there is no literature on the relative contribution of the indirect protective effect of an intervention on a very nearby (40 meters) versus far-off (300 meters) household, it is biologically reasonable to assume that the former is greater. The choice of a high cut-off (1 kilometer) was motivated in part by the fact that individual mosquitoes have been found to travel significant distances: a 2019 study, albeit of a different sub-species, found an average distance of nearly a kilometer before re-trapping, with some mosquitoes having traveled 3 kilometers from their release site (Webb and Russell, 2019). Both direct and indirect protection were assigned a value on a 0 to 1 scale, with 1 being maximum protection (the day of IRS) and 0 being unprotected (never fumigated or >365 days since fumigation). These values were then decayed by time since fumigation ((365 - days) / 365) and weighted for each observation by the distance to the area estimated (1 - distance in kilometers). The protection score is the simple sum of the community and individual protection values.

Lagged precipitation is an important determinant of malaria activity. Though some studies use relatively long lags (as many as 4 months, (Matsushita et al., 2019;

Stebbins et al., 2018)), most have found that a 1-2 month lag is sufficient for predicting malaria outbreaks (Jusot and Alto, 2011; Matsushita et al., 2019; Stebbins et al., 2018; Wardrop et al., 2013), especially in relatively warm climates. Accordingly we employed a 15-60 days rolling lag of cumulative millimeters of precipitation.

Econometric model

Our model specification is intentionally simple. We understand the risk of absenteeism to be influenced by two factors: malaria seasonality (captured in our lagged precipitation term, which spans from 15 to 60 days prior to the date in question) and "protection" (ie, the time-specific summed IRS in the vicinity, weighted by distance, as described in the previous section), and can be conceptualized formulaically as follows:

$$log(1 + Y_{it}) = \beta_0 + \beta_1 \, IRS\,protection_{it} + \beta_2 \, Precipitation\ lag_t + \alpha_i + \upsilon_{it}$$

Y_{it} is the probability of absence at time t for individual i. $IRS\,protection_{it}$ is the worker's day-specific "protection" level as conferred by the IRS status of her and others' households as well as her own household's fumigation, and $Precipitation\ lag$ is 15-60 day lagged cumulative precipitation. α_i represents the time invariant worker fixed effects. υ_{it} is the error term.

We assume that the marginal benefits of IRS are likely to be different for different worker types. Fumigation can be reasonably expected to be greater for those who spend more time in that area (ie, permanent workers). By the same token, those with higher socioeconomic status are likely to benefit less from fumigation because of the fact that they are more likely to have available other malaria prevention measures (screened doors and windows, repellents, air conditioning, insecticide-treated nets). It is plausible that different worker roles (field vs factory, for example) may have differential exposure to malaria-transmitting mosquitoes based simply on the amount of time spent outdoors. Finally, it is reasonable to assume that the effect of IRS on preventing absence might be greater among those who reside continuously in the IRS-treated area (permanent workers) than among those who reside there intermittently (migratory temporary workers). Given these probable differences in IRS' effect by worker type, we estimate the model separately for three distinct groups: (i) permanent field workers; (ii) permanent non-field workers; and (iii) temporary workers

Our approach towards return on investment (ROI) can also be described in a straightforward fashion…

$$R = \frac{P_w - S_{wa} - S_{wc}}{P_w}$$

…where R is the return on investment, P is the malaria control program's total operating cost, w refers to costs at the per-worker level, S is saving, a refers to savings through avoided absences, and c refers to savings through avoided clinical encounters. We define the malaria control program as "profitable" from an investment standpoint if ROI is greater than 100%, ie if the savings associated with the estimated effect of IRS in prevented absences and reduced clinical costs is greater than the costs of the program's administration.

Reproducibility and ethical approval

All data processing and analysis were carried out in R (R Core Team, R: A language and environment for statistical computing) and all analysis code is freely available online (Brew, 2017). Ethical approval for this project was obtained from the Institutional Ethics Review Board for Health at the CISM (CIBS-CISM) prior to data collection.

4. Results

Effect of IRS on absenteeism

Figure 6 shows average monthly absenteeism as a function of time before and after IRS application. Immediately following IRS at one's own household, a worker's likelihood of absence drops significantly (figure 6, panel A). As one would expect if the mechanism by which IRS reduces absence is through reduced malaria infection, the effect of IRS during the low transmission season is significant, but far less substantial in effect size (figure 6, panel B).

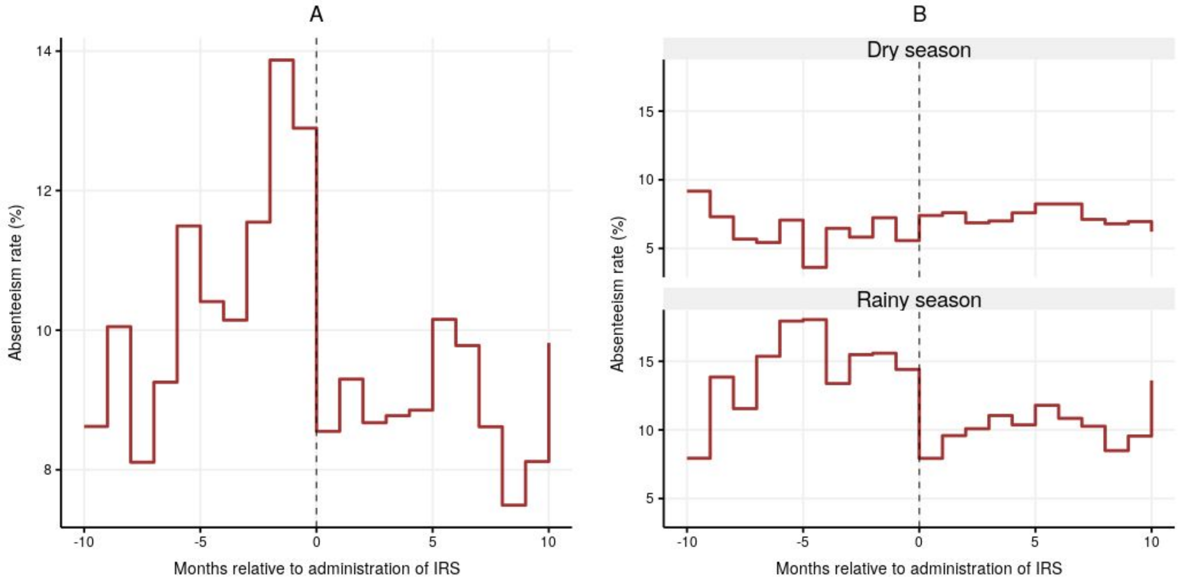

Figure 6 (i) Absenteeism before and after IRS administration for all workers who ever received IRS, (ii) The same, but segregated by rainy and dry seasons (defined here as above or below the median value of lagged precipitation)

Separate models were estimated for all 3 worker groups, and a fourth model was estimated with all groups combined. Model results (table 4) show that there are two clear archetypes. Among permanent workers, IRS administration is associated with a significant reduction in absenteeism, whereas this relationship is directionally ambivalent and statistically insignificant among temporary workers.

	Permanent field workers	Permanent non-field workers	Temporary workers	Non-segregated model
IRS protection	-0.028 (p = 0.001)	-0.035 (p < 0.001)	0.006 (p = 0.43)	-0.026 (p < 0.001)
Lagged precipitation	0.009 (p < 0.001)	0.005 (p < 0.001)	-0.002 (p < 0.001)	0.005 (p < 0.001)

Table 4: Linear fixed effects model with 1,933,715 observations, p < 0.001, R-squared of 0.076.

A more intuitive presentation of the reduction in risk of absenteeism associated with our model estimation than the above coefficients is the generation of predictions of absenteeism as a function of protection score, setting the other predictors (lagged precipitation and the worker-specific fixed effect) to the average for the entire study period and population, respectively (figure 7).

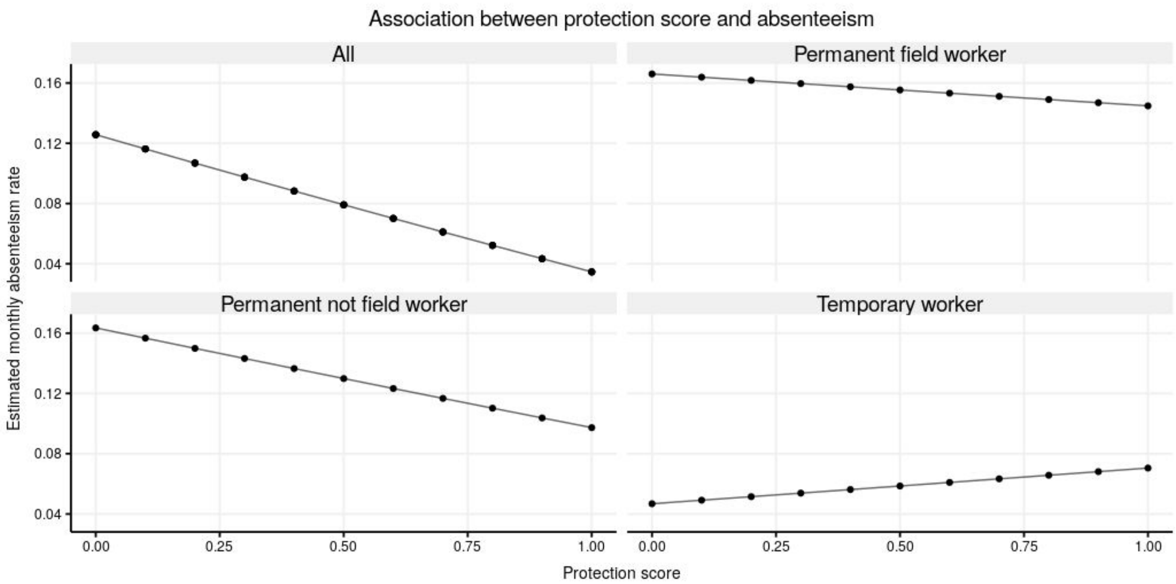

Figure 7: Predictions for absenteeism as a function of individual protection (color of line) and community protection (x-axis)

By the same token, we use predictions on simulations to estimate absenteeism as a result of different fumigation "strategies", including the counterfactual of no spraying at all (which, when juxtaposed with the observed absenteeism during our study, can be understood as the effect of the program itself).

The number of absences prevented by Maragra's IRS program can be understood as the number of absences which would have occurred had the program not existed minus the number of absences which did occur. We estimate the "would have" scenario by simply setting all worker “protection” scores to 0 (ie, as if neither they nor their neighbors received any IRS protection), and then generating predictions using the linear fixed effects model previously described ($log(1+Y_{it}) = \beta_0 + \beta_1 \, IRS\ protection_{it} + \beta_2 \, Precipitation\ lag_t + \alpha_i + \upsilon_{it}$, wherein all right-hand side variables are known from the previous model estimation, and B_1 is set to zero). In reality, this is over-stylized: the government carries out occasional IRS campaigns which would provide some protection to some workers. Nonetheless, ignoring the government programs is compatible with the hypothetical counterfactual from an investment perspective (ie, some IRS exposure due to government programs constitutes "business as usual").

The panel consisted of 1,933,175 worker-days. For the purposes of estimating the model, we removed observations from workers who lived off-site (cognizant of the fact that workers living at the perimeter of the site likely benefited indirectly from the firm's IRS activities). Of the remaining 588,205 eligible worker-days, we observed 60,452 absences (an absenteeism rate of 10.28%). Using the above approach, we estimate that we would have observed 84,815 absences had it not been for the firm's IRS program, for a total of 24,363 avoided absences. This translates to an overall reduction in absenteeism from 14.4% (without its IRS program) to the observed 10.28%.

Our panel was imbalanced in that it underrepresented temporary workers' true share of working days, since temporary workers' observations were removed for 2013 and 2016 (see "Methods").This has an inflationary impact on the absenteeism reduction estimate since the absence-preventing effect of IRS is greater among permanent workers. To offset this bias, we estimate year-specific reductions in absenteeism for each type of worker, and then weight those averages by the corresponding share of working days for the years for which full data is available. Doing so suggests an average annual reduction in absenteeism from 16.8% to 12.6% among permanent fieldworkers, a similar reduction of 16.4% to 11.4% among permanent non-fieldworkers, and a less significant reduction in absenteeism from 5.4 to 4.1% among temporary workers. Overall, given the firm's make-up of days worked by worker category, this equates to a total of 6,475 averted absences per year, a reduction from a counterfactual 13.0% absenteeism (were the IRS program not to exist) to the observed 9.3%. In total, the program is estimated to have prevented on average 1 absence for every 27 worker-days.

Return on Investment

We divide program costs by the number of prevented absences to estimate the cost per prevented absence. The average annual operating budget of the firm's malaria control program is 68,984 USD. Divided by the approximately 6,475 avoided the program is estimated to avoid annually, the firm's cost per absence avoided is approximately $10.65. However, it is important to note that averted absences were not randomly distributed: the absence-preventing effect of IRS is higher in permanent workers (who are also more highly paid) relative to temporary workers, not only at the individual level but even more so when aggregated because (a) the total number of eligible worker-days is greater among permanent workers, and (b) the baseline absenteeism among permanent workers is greater.

Wage data was only partially available from the firm. Wages for certain “grades” (skilled workers and management) were not available, and in some cases worker grades themselves were missing in the administrative data. Accordingly, we cannot carry out an exact estimation of productivity losses using person-level wages as a proxy for productivity. Instead, we carry out a sensitivity analysis of return on investment as a function of the productivity (ie, daily wage) of temporary and permanent workers (figure 7), aggregating both permanent field and non-field workers given the similarities in the estimated effect of IRS on each groups' absenteeism.

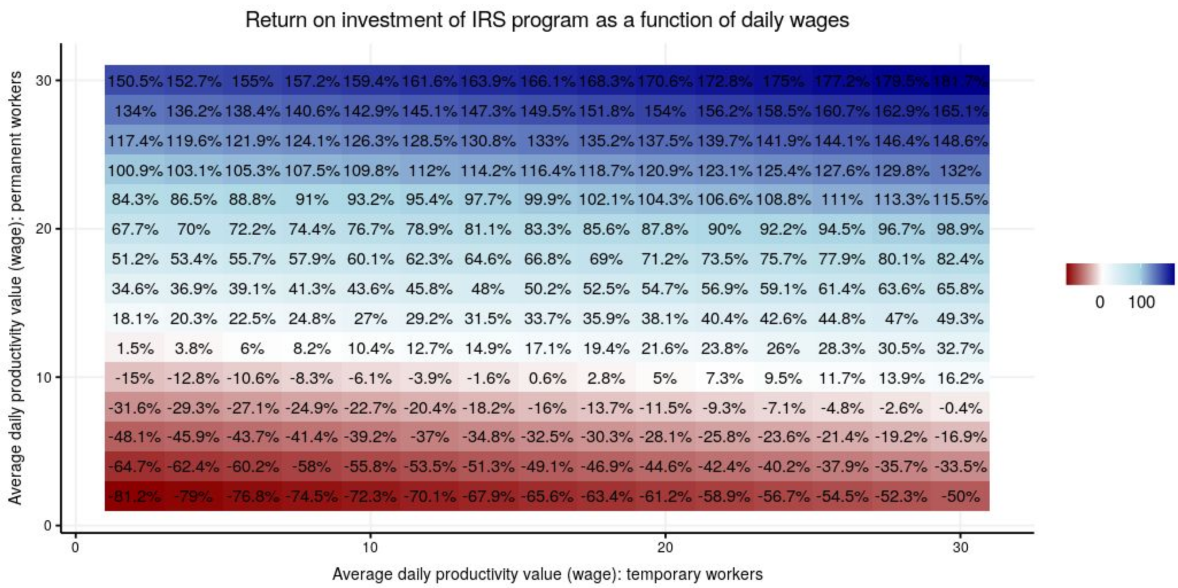

Figure 7: ROI as a function of daily estimated average productivity of temporary and permanent workers, given Maragra’s ratio of temporary to permanent workers.

Of course, the above is subject to the percentage of workers of each type. Relative to many firms, the percent of eligible working days at Maragra among permanent workers is quite high (68%). Figure 9 shows different scenarios in which that ratio were to change.

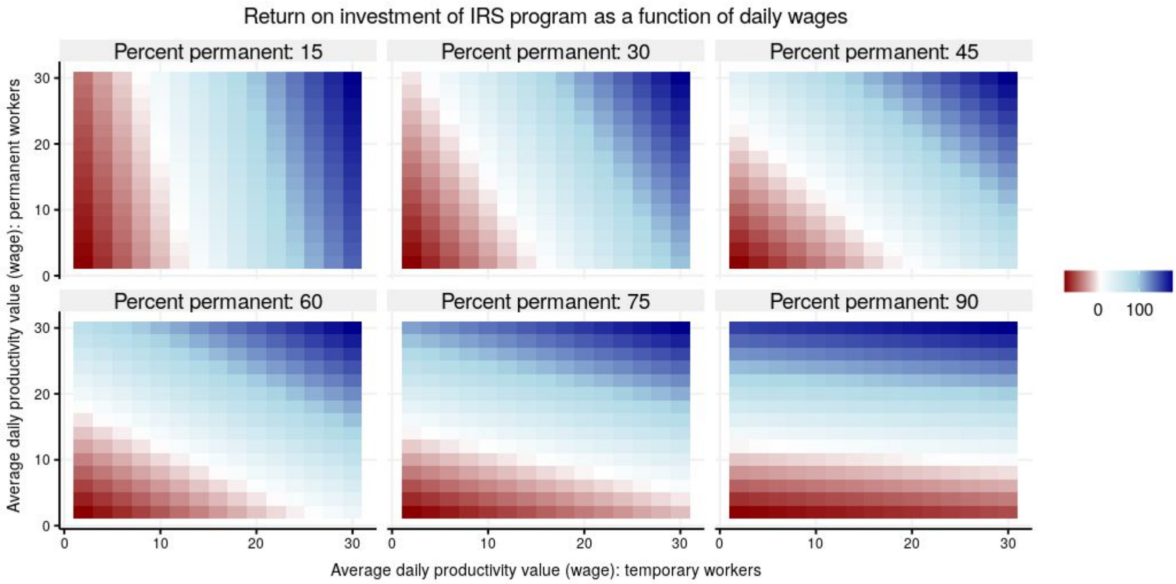

Figure 9: *ROI as a function of daily estimated average productivity of temporary and permanent workers, given Maragra's, faceted by percentage of workers which are permanent*

Given the non-random missingness in wage data, there is no way to estimate exactly whether the firm's IRS program is associated with a positive ROI. However, given that the large majority of temporary workers are cane-cutters, who earned on average \$5-9 USD per day, for the program to be profitable, average daily productivity (ie, daily wages) among permanent employees would have to be approximately \$10 USD or less. This does not take into account the fact that, on average, for every 80 absences, the firm's clinic treats a case of malaria, with a cost of treatment estimated to be \$22 (\$0.28 per absence).

Alternative scenario analysis: policy simulations

In previous sections, we showed that the counterfactual of no firm IRS operations would have lead to approximately 6,475 additional annual worker absences over the course of the four year study period. However, though the most useful for calculating ROI, the "zero" IRS strategy is not the only plausible counterfactual. Two others also exist. First, one could employ a "time-optimized" strategy in which an identical amount and chemical distribution of total insecticide is used, but deployed in such a way that "overprotection" (ie, more than 1 spraying in a 6 month period) does not take place and the saved insecticide is applied to houses which were "underprotected" (ie, more than 6 months had elapsed since the last fumigation). Second, a "gold standard" strategy could be employed in which no house were ever permitted to enter into an "underprotected" status, even if this meant using more insecticide.

Relative to the counterfactual absenteeism rate of 13% associated with no IRS program, the marginal benefits of the hypothetical optimized policies did not show significant improvement of the observed reduction in absenteeism to 9.3%. The "time-optimized" approach was estimated to reduce absenteeism to 8.9%, whereas the "gold standard" approach would have further reduced absenteeism to 8.8%. The fact that the marginal gains from optimizing IRS timing are minor suggests that there may be an unobserved "wisdom" in the current practice of non-systematic fumigation operations, such as timing based on local epidemiological conditions or identification of other risk factors.

The “gold standard” strategy (ensuring all on-site households were < 6 months from the most recent fumigation at all times) would have led to the greatest reduction in absenteeism. Its similarity to the “time-optimized” strategy can be explained by unnecessary re-sprayings. In other words, by simply re-allocating the insecticide used for the approximately 45% of fumigations which occur at a household which had already been fumigated in the previous 6 months, a situation similar to the gold standard could be achieved using an identical amount of spray. It is worth noting, however, that the “gold standard” strategy of 6 months re-application is based only loosely on estimates of insecticide decay (Sadasivaiah et al., 2007) and any policy recommendation stemming from these simulations should first be field-tested.

Robustness and generalizability

Three principal concerns call into question the results of our analysis. First, the application of IRS to a worker’s house may be endogenous. It is reasonable to suspect that the assignment of IRS to households is not random, but rather that IRS was applied more frequently to houses which had already seen a malaria case. In this case, our estimated effect of IRS on absenteeism would likely be underestimated, with the post-IRS absenteeism rates actually having declined from a greater pre-IRS absenteeism rate than otherwise suggested.

To check for this, we estimate the odds of absenteeism as a function of receiving IRS 10 days in the future. If IRS applications were indeed endogenous, we would expect absenteeism to be elevated during this period (since the increase in absenteeism would be theoretically responsible for the application of IRS), a situation which would require further statistical adjustment. If, on the other hand, there is no endogeneity, we would expect absenteeism in the 10 day period prior to IRS administration to be similar to other pre-IRS absenteeism (adjusting for seasonality and job type, etc).

The below shows our robustness check for all cause absenteeism.

Variable	Estimate	Lower	Upper	P value
(Intercept)	0.0662	0.0614	0.0711	< 0.001
10 days prior to IRS	0.9229	0.7300	1.1503	0.489
Malaria season	3.1173	2.9319	3.3156	< 0.001
Department: Factory	1.0944	1.0118	1.1841	0.025
Department: Field	0.5426	0.5036	0.5850	< 0.001
10 days prior to IRS:Malaria season	0.8172	0.6161	1.0908	0.165

The large P-value associated with the 10 days prior to the IRS variable's association with absenteeism suggests that endogeneity is not a significant concern.

The second concern is that our quantification of return on investment is distorted by the fact that we treat IRS operations as essentially linear in nature, when in reality economies of scale, in-kind purchases and other factors likely make the true cost-per-spraying convex. To the extent that this paper examined only one company - and not during a time of operational change - we cannot make any reliable inference regarding how costs would be expected to change as a function of program characteristics.

The third concern regarding robustness is our estimation of the IRS protection score. Our analysis assumes that the degree of protection conferred by fumigation declines linearly as a function of distance up to 1 kilometer away. In other words, the weight of a household 200 meters away is twice that of a household 600 meters away (weight being 1000 - meters / 1000). We believe that this approach better reflects actual indirect protection than the “hard borders” approach used in most studies, in which either a distance threshold is established, or natural village borders are used, to define an “in” versus “out” area for what constitutes community protection. That said, in order to see if our results were robust to the method used, we carried out the same analysis using a radial threshold of 400 meters. Though the magnitude of the coefficient for community protection is greater in the hard-threshold approach since it is effectively a binary variable (“in” vs “out”), the estimates are directionally similar for all groups using both the distance-weighted and hard-threshold (radial) approaches. This is consistent with the method being robust to minor changes in measurement.

5. Discussion and conclusions

We estimate that Maragra’s IRS program reduces absenteeism among workers by 3.7 percentage points (from 13.0% to 9.3%), and that the savings in terms of productivity outweigh the costs, with a program-wide return on investment of 100%, assuming daily wages of temporary workers to be approximately $7 and permanent workers to be approximately $10. Our analysis was intentionally restrictive. Though much of the benefits of preventing malaria are accrued outside of the firm (savings to the public health care system, improvements in health and well-being, increases in societal economic efficiency and capital accumulation, etc.), we ignored these benefits, focusing only on those savings which accrued directly to the firm. This point of view - the narrow, profit-driven perspective of an "investor" - is at odds with the public health mindset, and most of the research on the economics of malaria. In fact, when the profit perspective is not ignored (as it usually is by public health researchers), it is criticized - often rightfully so - for failing to appropriately quantify the full costs of poor health.

But the investment perspective is useful. From the societal point of view, an investment perspective helps to identify those "win-win" opportunities in which improvements in health don’t come at a cost to the public sector. From the narrower firm’s point of view, a quantification of return on investment helps companies to identify those opportunities where corporate social responsibility and loyalty to shareholders intersect. And to the extent that profits and social good don’t always neatly coincide, identifying situations in which social responsibility has a negative return on investment is critical to informing policies around subsidies and to quantifying them efficiently.

To our knowledge, this is the first study which has quantified ROI of privately-managed malaria control activities from a firm/investment perspective. This contributes to the body of knowledge regarding the economics of malaria both methodologically (by structuring an identification strategy which allows for the quantification of in-firm positive externalities, ie. immunity conferred upon neighbors through the application of IRS) as well as conceptually (restricting analysis to a profit-centric perspective solely).

We believe that this study may have implications both for policy and business. The fact that ROI was positive may incentivize firm shareholders to take a less cautious approach to malaria control. By the same token, policymakers should consider working with private firms to ensure best practice in regards to the administration of malaria control programs, since both stakeholders (the firm and the public which policymakers represent) stand to benefit. The potential for a positive ROI should have particular impact in contexts in which private firms cover large areas and employ many people. This is the case not only in Maragra, but in the African sugar industry generally, as well as other agricultural and extractive industries. Governments should work closely with firms with the shared goal of generating a return on investment to both the public and the private stakeholders. In areas where malaria control stands to be profitable from a private perspective, public resources could be restricted and appropriately directed elsewhere (areas where, due to the conditions, sparseness, or level of endemicity, malaria control is unlikely to be profitable).

Limitations

Our study is not without limitations. Our identification strategy was simple, using only two explanatory variables (protection and lagged precipitation), both of which relied on assumptions for their abstraction. Our protection variable combined an assumed linear decay in IRS' effectiveness over time with a similar assumed decline in its effectiveness over space. Both assumptions are based loosely on the literature regarding IRS's waning effect and mosquitoes' geographical range, but are almost certainly too simplistic.

We quantified absences, but data were not reliable enough to quantify productivity in finer terms. Tonnage of sugar processed would have been a more precise outcome, and would yield more direct estimates of return on investment. But firm data on processing was too aggregated to be of use for our modeling approach. And even if it were available, tonnage as a proxy for productivity would only be applicable to cane-cutters. Since we modelled absenteeism only, we may actually be *underestimating* the true effect of IRS on productivity, since it is reasonable to think that a worker who is ill may occasionally show up to work, but work in a less productive manner. By the same token, it is plausible that productivity losses at the aggregate level are greater than the sum of their parts: a missing worker on a factory assembly line may reduce the productivity of his colleagues, for example.

Though the sample size and window of observations were large, external generalizability is difficult to assess. Our distance-based method of quantifying community protection of IRS means that our estimates for ROI for any other context would be different, based on the density of the workers' residences. On the one hand, this is a strength of the approach: it means that both (a) timing and location of IRS application can be optimized and (b) identification of profitable vs. non-profitable IRS situations can be carried out *a priori*. On the other hand, the approach does not lend itself to straightforward "translation" to non-academic business settings, where ROI is best expressed in per unit terms.

Given the global push for malaria eradication, new approaches, opportunities, collaborators, and strategies need to be identified. Scaling up private sector involvement in fighting malaria may be an effective approach - in certain areas where due to geography, resources, or other reasons - the public sector has not been able to stem the tide of the epidemic. A private sector scale-up, though, requires hard evidence of the potential profitability of malaria control activities. In the case of this study, the evidence suggests that doing well and doing good can go hand-in-hand.

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